INL/CON-07-12981
PREPRINT

Initial Irradiation of the First Advanced Gas Reactor Fuel Development and Qualification Experiment in the Advanced Test Reactor

Advanced Nuclear Fuel Cycles and Systems - Global 2007

S. Blaine Grover
David A. Petti

September 2007

INITIAL IRRADIATION OF THE FIRST ADVANCED GAS REACTOR FUEL DEVELOPMENT AND QUALIFICATION EXPERIMENT IN THE ADVANCED TEST REACTOR

S. Blaine Grover[1] and David A. Petti[2]

Idaho National Laboratory, PO Box 1625, Idaho Falls, Idaho, 83415, United States of America,
[1]Tel: 208-526-4489, Fax: 208-526-2930, Email: Blaine.Grover@inl.gov
[2]Tel: 208-526-7735, Fax: 208-526-2930, Email: David.Petti@inl.gov

The United States Department of Energy's Advanced Gas Reactor (AGR) Fuel Development and Qualification Program will be irradiating eight separate tri-isotopic (TRISO) particle fuel (in compact form) experiments in the Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL). These irradiations and fuel development are being accomplished to support development of the next generation reactors in the United States. The ATR has a long history of irradiation testing in support of reactor development and the INL has been designated as the United States Department of Energy's lead laboratory for nuclear energy development. The ATR is one of the world's premiere test reactors for performing long term, high flux, and/or large volume irradiation test programs. These AGR fuel experiments will be irradiated over the next ten years to demonstrate and qualify new particle fuel for use in high temperature gas reactors. The experiments, which will each consist of six separate capsules, will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control for each capsule. The swept gas will also have on-line fission product monitoring to track performance of the fuel in each individual capsule during irradiation.

The final design phase for the first experiment was completed in 2005, and the fabrication and assembly of the first experiment test train (designated AGR-1) as well as the support systems and fission product monitoring system that will monitor and control the experiment during irradiation were completed in 2006. The experiment was inserted in the ATR in December 2006, and will serve as a shakedown test of the multi-capsule experiment design that will be used in the subsequent irradiations as well as a test of the early variants of the fuel produced under this program. The experiment test train as well as the monitoring, control, and data collection systems are discussed and the status of the experiment is provided.

I. INTRODUCTION

These irradiations and fuel development are being accomplished to support development of the next generation reactors in the United States. The AGR fuel experiments will be irradiated over the next ten years to demonstrate and qualify new particle fuel for use in high temperature gas reactors. The goals of the irradiation experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance and fission product transport models and codes, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing.[1,2] The experiments, which will each consist of six separate capsules, will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gas will also have on-line fission product monitoring on its effluent to track performance of the fuel in each individual capsule during irradiation.

The AGR fuel experiments belong to a category of experiments designated at the INL as instrumented lead experiments, which derives its name from the instrument leads utilized to provide continuous monitoring (and typically control) of experiment parameters during irradiation. Each instrumented lead experiment test train may contain several vertically stacked capsules, and is typically designed, as the AGR experiments were, for a specific irradiation position in the ATR. Therefore the design is unique for the irradiation position location and size, irradiation parameters (e.g. temperature, fluence, monitoring requirements, etc.) and the umbilical tube routing necessary to connect the experiment to the monitoring, control and data collection equipment. This paper discusses the design of the AGR-1 experiment and the progress and status to date on the experiment[3].

II. EXPERIMENT CAPSULES

The experiment test train for AGR-1 consists of six separate stacked capsules vertically centered in the ATR core. Each capsule has its own custom blended gas supply and exhaust for independent temperature control and fission product monitoring. Temperature control of the capsules is accomplished by adjusting the mixture ratio of two gases with differing thermal conductivities to control the heat transfer across an insulating gas jacket between the heat source (fuel fissions and gamma heating of capsule materials) and the relatively cold reactor coolant (52 ºC). Helium is used as the high (thermally) conductive gas and neon is used as the insulating gas.

A horizontal capsule cross-section at the top of the test train is shown in Figure 1 and a vertical section of a capsule is shown in Figure 2. The capsules are approximately 35 mm (1-3/8 inches) in diameter and 150 mm (6 inches) in height - including the plenums between adjacent capsules. Each capsule contains 12 prototypical right circular cylinder fuel compacts nominally 12.3 mm (½ inch) in diameter and 25 mm (1.0 inch) long.

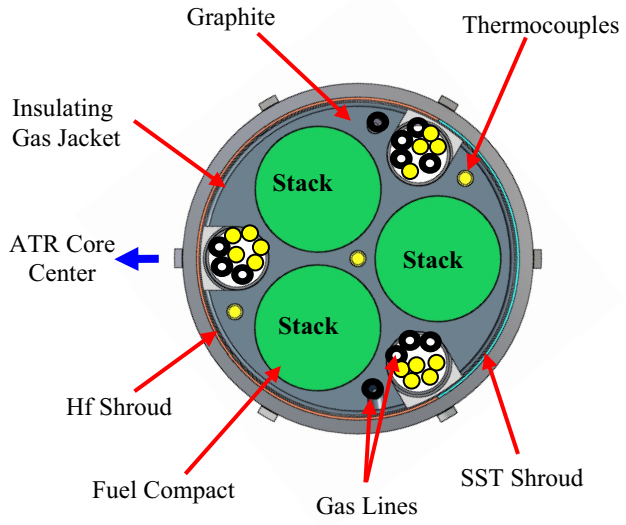

Fig. 1. Horizontal cross-section of an AGR experiment capsule

The fuel is comprised of 350 µm diameter Low Enriched Uranium (LEU) fuel kernels, which are covered with a layer of silicon carbide sandwiched between two pyrolytic carbon layers to make up the 780 µm nominal diameter TRISO-coated fuel particles. Next the fuel particles are over-coated with a thermo-set resin and pressed into fuel compacts that are then sintered to remove the volatile compounds in the resin. Each compact contains approximately 4,150 fuel particles with a mean uranium content of approximately 0.9 grams.

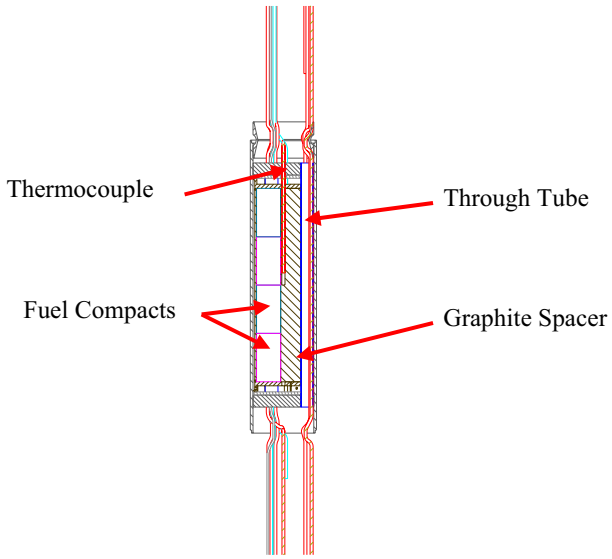

Fig. 2. Vertical section of an AGR experiment capsule

The experiment contains baseline fuel compacts as well as compacts made from three fuel variants with different coatings and process development variations. The compacts are arranged in four layers in each capsule with three compacts per layer nested in a triad configuration. A nuclear grade graphite spacer surrounds and separates the three fuel compact stacks in each capsule to prevent any fuel particles on adjacent compacts from touching each other, which could possibly cause a premature particle failure. Very thin (0.5 mm) graphite top and bottom end caps on the compacts prevent particle to particle contact between adjacent axial compacts. The graphite spacer also provides the inner boundary of the insulating gas jacket (approximately 0.25 mm to 1.0 mm thick depending on vertical location within the reactor core) for temperature control of the fuel during irradiation. Boron carbide was dispersed in the graphite spacer to serve as a consumable neutron poison. In addition to the boron carbide, a thin (0.25 mm thick) hafnium shield next to the outside capsule wall surrounds the two fuel compact stacks facing toward the center of the ATR core (stacks 2 and 3 shown in Figure 1). A thin (0.25 mm thick) stainless steel shield next to the outside capsule wall blankets the other fuel compact stack (stack 1 shown in Figure 1) located on the side of the capsule facing away from the ATR core. Stainless steel was used for this shield (versus hafnium) in order to minimize the effects on the neutron flux to these already lower powered fuel compacts while retaining the same insulating gas jacket to maintain the proper irradiation temperature. The neutron poisons were necessary to limit the initial fission

rate in the fuel and thereby provide a more consistent fission rate/power production during irradiation. As the boron carbide is consumed in the graphite, the fission rate in the fuel will reach a peak at about the mid-point of the irradiation. The fission rate will then slowly decrease as the fuel continues to burn-up. Reducing and controlling the initial fission rate in this manner decreased the ratio of the maximum to minimum heat generation rates in the fuel, which will provide better temperature control in the fuel over the length of the rather long two year irradiation. In addition to protecting the fuel, the graphite spacer has features machined to accommodate the thermocouples for measuring temperature within the capsule and the three through tubes containing the gas lines and thermocouples for adjacent capsules. The through tube locations were positioned very precisely in the top and bottom heads of the capsules and they were also given a very tight tolerance fit with their accompanying grooves in the graphite spacer. The through tubes were then utilized to precisely center the graphite in the capsule and space it at the proper distance from the capsule wall to provide the necessary gas jacket for temperature control. Since the through tubes will be in contact with the high temperature graphite throughout their length, one end (the bottom) of the tubes had to be fitted with a very tight (less than 0.013 mm) slip fit between the tubes and the capsule bottom head to prevent the significant difference in (axial) thermal expansion between the capsule shell and the tubes from causing excessive stresses in the tubes. These stresses would result in bowing of the tubes, which could put stress on the graphite spacer and possibly the fuel compacts. The tight slip fit was needed to severely limit and control any leakage of the temperature control gas between the tubes and the capsule head. To prevent possible cross contamination between the capsules, a small helium flow (total of 10 to 20 cc/min for all capsules) is introduced into the through tubes and plenums between the capsules to ensure any leakage between the tubes and capsule head is into the capsules.

There are nominally three thermocouples in each capsule (the top and bottom capsules have five and two thermocouples respectively for different reasons) located in the top, middle, and bottom areas of the graphite spacer measuring the temperature of the graphite. Since no metal could touch the fuel particles, the thermocouples measure the graphite temperature and the corresponding fuel temperatures are calculated. Flux wires were also installed in the graphite to measure both the thermal and fast neutron fluence. As indicated earlier, the outside diameter of the graphite establishes the inner boundary of the insulating gas jacket, and therefore very rigorous and closely integrated reactor physics and thermal analyses were necessary to establish the exact dimension for this diameter. Consequently, the outside diameter of the graphite spacer varies among the capsules depending on the flux value at the vertical location of the specific capsule within the ATR core. The boron carbide content in the graphite spacer is different in the top and bottom capsules than the other four capsules due to the vertical neutron flux gradient in the ATR core. The graphite was also carefully analyzed to ensure shrinkage and changes in its thermal properties during irradiation would not adversely impact the fuel or temperature control of the capsule.

An umbilical tube (termed a lead-out) houses and protects the gas lines and thermocouple leads from the experiment capsules to the reactor vessel wall penetration. Outside the reactor vessel wall, the gas lines and thermocouple leads are connected to their facility counterparts in the temperature monitoring, control and data collection system. The lead-out also vertically locates the experiment in the east large B irradiation position in the ATR core.

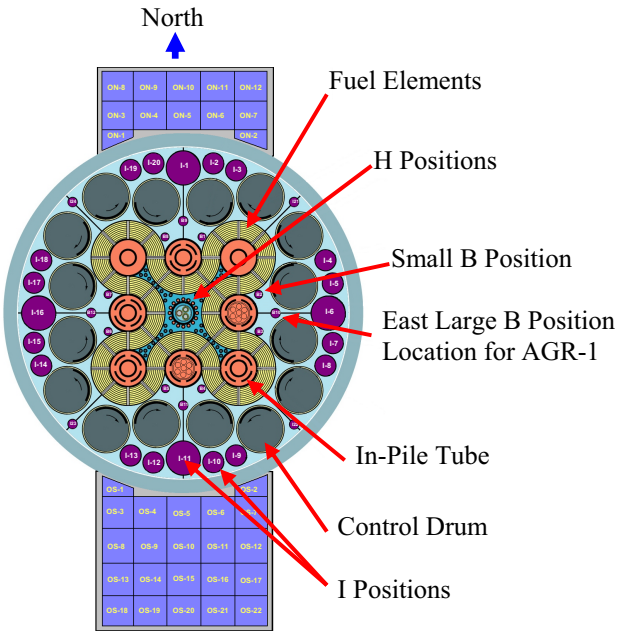

Fig. 3. ATR Core Cross-Section

The large B positions (38 mm or 1.5 inch diameter) were chosen for the AGR fuel irradiations due to the rate of fuel burn-up and fast neutron fluence accumulation in these positions providing an acceleration factor of between one and three times that expected in the Very High Temperature Reactor (VHTR). This acceleration factor was high enough to accomplish the irradiation within a reasonable time, but yet low enough to avoid possible premature fuel particle failures similar to those experienced in past highly accelerated particle fuel tests. In addition to limiting the acceleration factor, avoiding

contact between fuel particles and limiting the materials contacting the fuel compacts/particles to only graphite and the inert temperature control gas were done to prevent possible premature fuel particle failures. The irradiation time for the AGR-1 experiment was determined by the neutron flux rate in the large B position and the Fissions per Initial Metal Atom (FIMA) average burn-up goal of 18% for all fuel compacts, and a minimum of 14% for each fuel compact.[4] This requirement in combination with the slightly less than 20% fuel enrichment resulted in a rather long irradiation time, and (of course) a significantly reduced heat generation rate towards the end of the irradiation.

As indicated earlier, every effort was made to flatten the heat generation rate curve as much as possible to increase the controllability of the temperatures at the end of the irradiation. This controllability was necessary to meet the time-average volume-average temperatures of 1150 +30/-75 ºC for the irradiation while staying below the time-average peak temperature of 1250 ºC and maximum instantaneous peak temperature of 1400 ºC. These requirements provided some significant challenges in the design of the AGR-1 experiment and control systems.

III. TEMPERATURE CONTROL SYSTEM

The temperature of each experiment capsule is controlled by varying the mixture of two gases with differing thermal conductivities in a small insulating gas jacket between the specimens and the experiment containment. Helium and argon have been used in the past, and this combination provides a nice wide temperature control band for the experiments. However, argon could not be used due to the effects of the activated argon gas on the fission product monitors. Therefore, helium and neon, which is the typical gas combination currently used at ATR, is also being utilized in the AGR fuel experiments. Computer controlled mass flow controllers are used to automatically blend the gases (based upon feedback from the experiment thermocouples) to control the graphite spacer temperatures, which are analytically coupled to the fuel specimen temperatures. The gas blending system has a range of 2% to 98% of each gas (with the other gas making up the balance) allowing a very broad range of control. The gas system operates at low pressure ($\leq$ 0.2 MPa) with a nominal flow rate of 30 cc/min and a maximum of 50 cc/min. With these operating conditions, very small size (1.5 mm inside diameter) stainless steel tubing was used to minimize the delivery times between the mass flow controllers and the experiment and also between the experiment and the fission product monitors to a nominal value of 2 to 2.5 minutes. In addition, early in the irradiation, the mass flow controllers on each capsule were “tuned “ to adjust the time constant between feedback from the capsule thermocouples and any associated gas mixture changes to avoid temperature fluctuations during normal operations and over/under shoot on achieving target temperatures on reactor start-ups.

The temperature measurements are taken with three thermocouples in each experiment capsule, one of which is designated as the control thermocouple. In the event the control thermocouple fails open (as indicated by a significant increase in resistivity); the designated primary back-up thermocouple will automatically be switched to be the new control thermocouple. The thermocouples typically used at ATR are 1.6 mm (0.062 inch) sheath diameter type K, with high purity magnesia insulation. However, due to the very high thermocouple temperatures (up to 1070 ºC) coupled with the relatively long irradiation (approximately two years); there was concern on the survivability of the thermocouples. Type C thermocouples were considered, but it was felt there would be too much transmutation in the thermo-elements due to their high neutron absorption cross sections. Type N thermocouples were also considered, but they have very similar temperature limitations to the type K thermocouples. To ensure the best survivability of the thermocouples used in the AGR irradiations, a selection of the most promising long life type K and type N thermocouples were purchased and tested in a thermal mock-up of the AGR irradiation conditions. In addition, several INL developmental (molybdenum-niobium) thermocouples were also included in the thermal mock-up testing to determine how they would survive the irradiation conditions.[5] The thermal testing was conducted for four months, and several low temperature cycles were also included in the testing to represent the reactor outages that will be experienced by the thermocouples during the experiment irradiation. In order to support selection of the thermocouples for the AGR-1 experiment, the test was conducted at the highest anticipated thermocouple temperatures during irradiation. The performance of the different thermocouples at this high temperature was then compared, and one of the Type N thermocouples and the INL developmental thermocouples were selected for use in the experiment. The Type N thermocouples are utilized in the coolest portion of the capsule (away from core center), and the INL developmental thermocouples are used in the higher temperature positions within the capsule (towards core center).

In order to minimize temperature changes and maintain the temperature as constant as possible, the temperature control gas system provides a continuous flow to each specimen capsule. Monitoring this continuous gas flow for fission gases can provide valuable

information on the fuel performance during irradiation and this function is discussed in the next section of this paper. Alarm functions call attention to circumstances such as parameters (e.g. temperatures, pressures, etc.) being outside of the established values or gas bottles requiring replacement. The control system conducts an automatic gas verification to assure the correct gases are connected to the supply ports in the system prior to allowing a new gas bottle to be placed into service to prevent unplanned temperature excursions. Helium purges to cool the individual specimen capsules are under automatic control in the unlikely event that measurement or control of the capsule temperature is lost. Manual control capability is also provided at the gas blending panels to provide helium purge in the event of a computer failure, and the system will automatically switch to helium purge on a power failure to the mass flow controllers. Data acquisition and archiving are also included as part of the control system function. Real time displays of all temperatures, all gas mixtures, and all alarm conditions are provided at the operator control station and at the experimenter's monitor located in the reactor building. All data are recorded once every minute, time stamped and archived to removable media. The control processor will record these values in a circular first-in, first-out format for a minimum of six months.

IV. FISSION PRODUCT MONITOR

Fission gases are the most common materials monitored in lead experiment temperature control exhaust gases, and the AGR fuel experiments are no exception. The experiment flow path is shown in Figure 4.

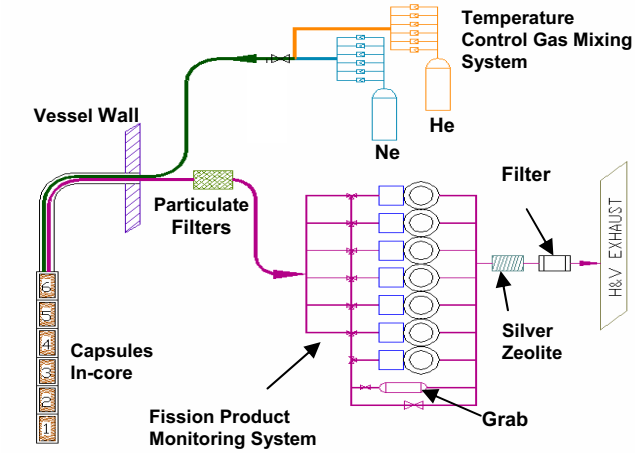

Fig. 4. AGR-1 Experiment Flow Path

The outlet gas from each capsule is routed to individual fission product monitors specifically designed for the AGR series experiments. The capsule outlet flows can be rerouted to an online spare monitor if any monitors experience detector or other failures. There is also the capability to take a grab sample of the effluent gas from each capsule. The fission product monitors consist of a spectrometer for identifying and quantifying the fission gas nuclides and a gross gamma detector to provide indication when a puff release of fission gases passes through the monitor. The gross gamma detector also provides the release timing. With the combination of a gross gamma detector and a spectrometer being continuously on-line, the gross gamma detector results can be scanned quickly to establish which portions of the voluminous spectrometer data need to be closely scrutinized. A puff release of fission gases typically indicates when a TRISO fuel coating failure may have occurred. Through identification and quantification (with uncertainties) of the isotopes, the spectrometer can be used to determine the isotopic release to birth ratio (with uncertainties) of the fission gases being detected. The determination of the release to birth ratios can establish whether a new TRISO fuel coating failure has occurred or if the fission products are merely being released from an existing failure or tramp contamination on the outside surface of the fuel particles. These details can be very important in the qualification of fuel especially in small TRISO particle fuels, where a few random particle failures are anticipated and need to be tallied very accurately to support statistical qualification of the fuel. The system was designed and response modeled to detect and quantify each individual fuel particle failure up to and including a very unlikely 250th fuel particle failure.

The spectrometers used for the AGR fuel irradiations are liquid nitrogen cooled High Purity Germanium (HPGe) detectors, because of their well-established capabilities and reliability. The spectrometers acquire spectra on a multi-channel analyzer and the spectra are analyzed for all expected fission products. In order to increase the sensitivity of the system, especially on the absolute quantity of fission products, the effluent gases are collected in a relatively large 50 cm^3 thin wall gas detection chamber filled with baffles to thoroughly mix and slow the movement of the gas in front of the germanium detector. The use of cryogenically cooled traps could also be employed to collect and concentrate the fission gases even more; however, there are no plans to implement this option on the first AGR fuel experiments. The type of gross gamma detectors utilized in the fission product monitors at ATR have varied from ion chambers to the present sodium iodide (NaI) crystal scintillation detectors currently used in the AGR fuel qualification tests. The shift was made from ion chambers to scintillation detectors to increase the sensitivity and therefore relax the proximity requirement between the gas lines and the detector. The NaI detectors are set for a low energy threshold of approximately 60 KeV and then all events above that value are scaled. Activated neon (Ne-

23) from the temperature control gas can raise the detector background using this approach, however, it is also felt this approach provides the greatest fission gas signal and thus optimizes the signal to noise ratio.

V. EXPERIMENT ASSEMBLY

Various different tests were conducted to support the test train fabrication and assembly. High temperature testing of the most promising candidate thermocouples was concluded in early April 2006 to support selection of the actual thermocouples used in AGR-1. A mixture of the best performing Type N commercial and INL developmental molybdenum-niobium thermocouples were selected for use in AGR-1. Testing on the gas leakage through a very tight slip fit between the through tubes and the capsule bottom heads was completed and the leakage experienced in the mock-up testing confirmed the design calculations used in sizing the clearance on the through tubes. Testing was also conducted on a multitude of capsule assembly processes (i.e., clearances, welding, brazing, etc.) to ensure the assembly of the test train could be accomplished as designed.

It was recognized during initial fabrication of the test train components that nickel (and possibly chromium) from Inconel, being planned for use in the through tubes and thermocouple sheaths, may migrate through the graphite spacer to the fuel compacts at the very high temperatures of the experiment irradiation. This metal migration to the fuel compacts could then possibly cause particle fuel failures. In order to prevent this condition, all materials in contact with the graphite spacer were changed to either molybdenum or niobium. This change resulted in the need for braze procedures to seal these different materials to the stainless steel capsule top heads. Development of these braze procedures as well as the stainless steel welding procedure for the automatic weld lathe used for the capsule welds were accomplished in accordance with the INL weld program as well as the AGR program requirements.

During the assembly of the actual test train, quality assurance personnel were involved in all of the special processes such as welding, brazing, specimen insertion, etc. They also performed various quality assurance tests such as weld inspection, helium leak detection, thermocouple continuity, etc. to ensure the test train was assembled in accordance with the drawings and the American Society of Mechanical Engineers (ASME) NQA-1 2000 requirements.

Assembly of the AGR-1 experiment test train was completed in September 2006, along with the installation of the fission product monitors and modifications of the existing temperature control gas system being utilized for the AGR irradiations. Modifications of the temperature control gas system were necessary to customize the system for use in the AGR irradiations.

VI. EXPERIMENT IRRADIATION AND STATUS

The experiment was inserted in the east large B position (B-10) of the ATR core in mid December 2006. Final flow testing of the temperature control and fission gas monitoring system installations were accomplished after the experiment had been inserted. Irradiation of the experiment was initiated on December 24th, and will continue for approximately two years to reach the 18% FIMA burn-up goal for the fuel compacts.

Moisture was detected in the exhaust gas upon reactor start-up when irradiation of AGR-1 was initiated. This condition was anticipated to occur from out-gassing of trapped moisture from the graphitic components as well as moisture trapped on the surfaces of the low temperature stainless steel components in the control gas system. To minimize this condition, precautions had been taken to eliminate as much moisture from the experiment capsules as possible by repeatedly evacuating and back filling with dry helium gas, followed by final pressurization with helium and sealing of the test train until final connection to the control gas system. In addition, purging of the control gas system prior to connection of the experiment was conducted, and the capsule temperatures were maintained at 400 to 500 ºC to prevent moisture in the control gas from causing undue oxidation of the graphitic material in the capsules (in both the graphite spacer and the fuel compacts) during start-up of the experiment. Upon further investigation, it was determined the moisture source was from leaks in the gas system piping downstream of the experiment but upstream of the moisture detector. These leaks were eliminated during the first outage of the experiment initial irradiation.

The performance and sensitivity of the fission product monitor has been excellent. During initial start-up of the experiment, the system detected activated Ar-41 from the small amount of air trapped in the system during connection of the experiment to the control gas system and air trapped within the rather porous graphite spacer and fuel compacts. It has also continued to detect activated Ar-41 from the small amounts of trace argon impurity in the Ultra High Purity grade helium supply gas used in the control system. Very low levels of fission gases (from the anticipated very low level tramp contamination on the outside of the fuel) have been measured and recorded by the fission product monitor system which has demonstrated both the sensitivity of the system as well as the integrity of the fuel.

Testing of the transport time between the capsules and the fission product monitors was conducted using the ability of the fission product monitors to detect the short lived (37.2 second half life) activated Ne-23 gas from the temperature control system. During the experiment design, the gas lines were sized to obtain a 2 to 2.5 minute delay between the experiment and the fission product monitors to allow decay of the activated neon without allowing too much decay of the short lived fission gases (of interest). The delay time was established by selecting a flow rate (e.g. 30 cc/min) and then limiting the amount of gas volume in the lines and equipment (e.g. valves, filters, detectors, etc.) to obtain the desired time. Verification testing of the delay time between the experiment and fission product monitors was performed while the experiment was on full helium flow to the capsules. A small amount of neon (e.g. 2 cc/min) was introduced to a single capsule and the time between the gas introduction and it's detection by the fission product monitor was measured. The measured times are within 20% of the calculated values, and better agreement is anticipated once measurement of actual gas volumes of various gas line equipment is completed. It has also been recognized that an additional length of delay line may be necessary to prevent excessive amounts of the activated Ne-23 gas from affecting the fission product monitor during operation when high concentrations of neon gas are needed to maintain the capsule temperatures.

As indicated earlier, cross flow between the six capsules in the test train was a serious concern and possibility as a result of incorporating the slip fit between the capsule bottom heads and the through tubes. A slip fit was utilized instead of a seal weld at this juncture since a fixed connection would cause excessive axial thermal expansion stresses between the tubes and the capsule wall. In order to prevent cross flow between capsules via the slip fit, the operating plan was to introduce a small helium flow (10 to 20 cc/min) into the lead-out cavity which communicates with the plenums between all six capsules. The purpose of the helium flow into the lead-out was to establish in-leakage to all six capsules and thus prevent any leakage from the capsules into the lead-out that could then possibly leak into a different capsule. During initial operation, it was confirmed that cross flow between the capsules had been prevented using this process. The prevention of cross flow between the capsules was first demonstrated by higher indicated flows in the exhaust lines than the supplied inlet flow to each of the six capsules. The fission product monitors were used to verify this conclusion and to determine the minimum necessary helium flow to the lead-out by introducing a small amount of neon gas into one capsule at a time and then observing the amount of activated neon detected in the test capsule as well as all of the other capsules. During this testing, the flow rate to the capsules was set at the nominal 30 cc/min flow rate, which had earlier been determined to provide a sufficient amount of the activated Ne-23 gas to the fission product monitor. By starting with a relatively high helium flow (e.g. 20 cc/min) to the leadout, and then slowly decreasing this flow until neon was detected in at least one capsule other than the test capsule, the minimum leadout flow was established for each capsule.

Once the moisture had been eliminated and the minimum flow to the leadout had been established, then the temperature of the experiment was raised. Initially, the design temperatures could not be achieved even with 100% neon flow due to the boron carbide content in the graphite. However, as anticipated, as the boron started to burn out in the graphite, the temperatures of the fuel compacts continued to rise. The design temperatures in all but the bottom capsule were attained at the end of the second ATR cycle of irradiation. The bottom capsule had not achieved adequate boron depletion at that time to attain design temperature. However, this condition will be remedied with further irradiation.

The final testing/calibration performed on the gas control system was tuning the mass flow controllers. This testing was accomplished after the experiment was brought to temperature. One capsule was reduced from full neon flow to 50% neon and 50% helium, and allowed to stabilize. A temperature was then chosen that would require approximately 75% neon, and the temperature change was requested from the temperature control system. The control system response was monitored and the mass flow controllers were adjusted as needed to minimize any under or over shoot in reaching the requested temperature. The process was repeated until the response on the temperature change for capsule was deemed acceptable. This activity was then repeated until all six capsules had been tuned.

VII. CONCLUSIONS

Fabrication and assembly as well as initial irradiation of the experiment has provided some valuable insight into the design and operating characteristics of the test train as well as the temperature control and fission product monitoring systems. It is anticipated that continued irradiation of the experiment along with continued operation of the temperature control and fission product monitoring systems will produce more valuable insights and lessons learned that may be applied to the future AGR experiments. These insights and lessons learned from AGR-1 can then be utilized to improve the experimental results and data from the future AGR irradiation experiments to support qualification of particle fuel for use in high temperature gas reactors

ACKNOWLEDGMENTS

This work was supported by the United States Department of Energy (DOE) under DOE Idaho Field Office Contract Number DE-AC07-05ID14517. The author would like to express gratitude to Dr. M. A. Feltus and J. K. Hartwell for reviews and support in preparing this paper.

REFERENCES

1. G. L. Bell, et al, "Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program", Oak Ridge National Laboratory Report ORNL/TM-2002/262, April 2003.

2. D. A. Petti, et al, "Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program", Idaho National Laboratory Report INL/EXT-05-00465, Revision 1, August 2005.

3. S. B. Grover, "Final Assembly and Initial Irradiation of the First Advanced Gas Reactor Fuel Development and Qualification Experiment in the Advanced Test Reactor", Proceedings of the International Congress on Advances in Nuclear Power Plants, Paper 7035, Nice, France, May 13-18, 2007.

4. J. T. Maki, "AGR-1 Irradiation Experiment Test Plan", Idaho National Laboratory Report INL/EXT-05-00593, August 2005.

5. J. L. Rempe, et al, "Evaluation of Specialized Thermocouples for High-Temperature In-Pile Testing", Proceedings of the International Congress on Advances in Nuclear Power Plants, Paper 6068, Reno, NV, USA, June 4-8, 2006.